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Determination of Zero-Dispersion Wavelength in Optical Fiber Using Four-Wave Mixing

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Abstract

Wavelengths of measured maximum four-wave mixing efficiency in optical fiber are compared to zero-dispersion wavelengths measured with a highly accurate frequency-domain phase shift technique. The average absolute discrepancy between the two wavelengths determined on fifteen fibers is 0.19 nm; for an average pump-probe spacing of 5.9 nm, the average spectral width of the four-wave mixing efficiency curve is 0.45 nm.

I. Introduction

Four-wave mixing (FWM) is a parametric process that involves the interaction of four optical waves in a material.[1] The efficiency of this process depends on the nonlinear susceptibilities of the material, the light intensities, and phase matching between the light waves. In optical fiber optimal phase matching for FWM occurs at or near the zero-dispersion wavelength.[2] In this letter, we describe measurements of partially degenerate four-wave mixing efficiency near the zero-dispersion wavelength of several different fibers. In partially degenerate four-wave mixing the pump provides two of the four optical waves at the same optical frequency. The other two waves are the probe and the generated anti-Stokes light. With the probe light fixed at a given wavelength, we determine the pump wavelength which gives maximum anti-Stokes light intensity in the zero-dispersion wavelength region of the fiber. We compare this pump wavelength with accurate measurements of the zero-dispersion wavelength using the frequency-domain phase-shift technique.[3,4]

II. Experiment

The experimental configuration for obtaining FWM efficiency is shown in Fig. 1. Two tunable lasers provide the pump and probe lights. The pump laser is amplified with an erbium-doped fiber amplifier (EDFA) to a power of +10 dBm. The probe laser light at -3 dBm is mechanically chopped to allow narrow-band detection of the FWM signal with lock-in amplifier techniques. Light from each source passes through an optical bandpass filter to minimize the amplified spontaneous emission (ASE) light, which can overwhelm the FWM signal, and polarization controllers are used to bring the polarization states into coincidence. The pump and probe lights are combined in a fused-fiber coupler, traverse the test fiber, and continue on to the photoreceiver. An additional optical bandpass filter with sufficient bandwidth (2 nm, full width at half maximum) for the wavelength scan is used at the photoreceiver to further isolate the FWM signal. The detected signal is passed to a lock-in amplifier. A computer automatically tunes the pump laser and acquires the FWM efficiency data. Laser wavelengths are measured with an interferometric wavemeter having an accuracy of 1 ppm.

Figure 2 shows the frequency-domain phase shift (FDPS) system, which has been described elsewhere.[3,4] The output of a tunable laser is intensity modulated by an integrated-optic Mach-Zehnder modulator. The phase of the RF modulation is monitored by a vector voltmeter after detection, amplification and filtering. The test fiber is temperature controlled to ±0.15 °C. Laser wavelength is monitored by a wavemeter and matched to corresponding relative group delays with a temporal resolution of 0.15 ps. This system can determine zero-dispersion wavelength with a precision of better than 0.025 nm (three standard deviations).[5]

III. Results

A typical FWM spectrum is shown in Fig. 3. We acquired this spectrum with an optical spectrum analyzer placed just after a 10 km dispersion-shifted test fiber while the pump was tuned to the fiber's zero-dispersion wavelength. During FWM efficiency measurements, the probe light exiting the test fiber is attenuated relative to the FWM light by the additional optical bandpass filter. This ensures good FWM signal isolation at the lock-in amplifier. A FWM efficiency curve of a 10 km dispersion-shifted fiber is shown in Fig. 4. Here the mid-scan pump-probe wavelength separation was about 5 nm and the efficiency curve had a full width at half maximum (FWHM) width of 0.36 nm. The experimental data are plotted with a theoretical curve.[2] Although the match is good, we believe the discrepancy between the theory and experiment is primarily due to the variation of zero-dispersion wavelength along the length of the fiber. Some test fibers exhibited more complicated FWM efficiency curves, but a clear FWM efficiency peak was still discernible in these fibers. In addition, by increasing the pump-probe wavelength separation, we were able to achieve narrower efficiency curves. A mid-scan pump-probe wavelength separation of 11 nm (the maximum possible with the filters available) gave a FWM efficiency curve width of 0.11 nm FWHM with no appreciable shift in peak FWM efficiency wavelength. Theoretically, the maximum efficiency wavelength does not depend on pump-probe separation; however, in practice there are trade-offs. A small separation results in a spectrally broad efficiency curve while a large separation enhances the unwanted effects of polarization mode dispersion. The 6 nm mid-scan separation chosen for most of these measurements represents a good compromise given the optical bandpass filters available to us.

Comparisons between peak FWM efficiency wavelengths and zero-dispersion wavelengths measured by the FDPS system for fifteen commercially available dispersion-shifted fibers are presented in Table I.

In all fifteen fibers a single FWM efficiency peak clearly dominated, and the absolute discrepancy between this peak and λ_0 was on average less than 0.19 nm. The mid-scan pump-probe wavelength separation was about 4-5 nm for fibers A-D, 11 nm for fiber E, and 6 nm for fibers F-O. The dispersion slope $dD/d\lambda$ measured with the FDPS system ranged from 0.069 to 0.0735 ps/(nm$^2\cdot$km) with an average of 0.0713 ps/(nm$^2\cdot$ km). The measured PMD at 1550 nm ranged from 0.03 to 0.11 ps/$\sqrt{\mathrm{km}}$ for fibers A-E, and varied as much as 30 % for each fiber measured over time.

Most fiber specimens were examples of recently manufactured high-quality fibers. Cut-back measurements on four equal-length sections of one fiber showed a linear increase in zero-dispersion wavelength of 1.5 nm over a length of 10 km.

TABLE I
COMPARISON OF PEAK FWM EFFICIENCY AND ZERO-DISPERSION WAVELENGTH

Fiber (length)	λ_{probe} (nm)	$\lambda_{pump\ @\ peak\ FWM}$ (nm)	$\lambda_{o\ FDPS}$ (nm)	$\lambda_{FWM\ Spec.\ Width}$ (nm, FWHM)	$\lvert \lambda_{pmp\ @\ pk} - \lambda_0 \rvert$ (nm)
A (5 km)	1550.27	1544.69	1544.68	0.44	0.01
B (12 km)	1555.21	1551.36	1551.38	0.48	0.02
C (12 km)	1556.40	1552.54	1552.70	0.41	0.16
D (10 km)	1558.26	1553.37	1553.45	0.39	0.08
E (10 km)	1560.14	1549.20	1549.21	0.11	0.01
F (20 km)	1555.14	1548.94	1549.17	0.21	0.23
G (10 km)	1555.14	1548.96	1548.86	0.32	0.10
H (10 km)	1555.14	1549.14	1549.44	0.36	0.30
I (5 km)	1555.14	1549.12	1549.04	0.51	0.08
J (5 km)	1555.14	1549.57	1549.87	0.35	0.30
K (2.5 km)	1555.14	1549.12	1548.83	0.78	0.29
L (2.5 km)	1555.14	1549.14	1549.22	0.67	0.08
M (2.5 km)	1555.14	1549.33	1549.56	0.55	0.23
N (2.5 km)	1555.14	1549.44	1549.94	0.48	0.50
O (1.25 km)	1555.14	1549.37	1549.82	0.67	0.45

IV. REFERENCES

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4. S. E. Mechels, J. B. Schlager, and D. L. Franzen, "Accurate zero-dispersion wavelength measurements in single-mode fibers: two frequency-domain methods," *LEOS 1995 Meeting Proceedings,* vol. 2, pp. 75-76, 1995.
5. S. E. Mechels, J. B. Schlager, and D. L. Franzen, "Accurate measurements of zero-dispersion wavelength in optical fibers," to be published in *J. Res. Nat'l. Inst. Stands. Technol.*

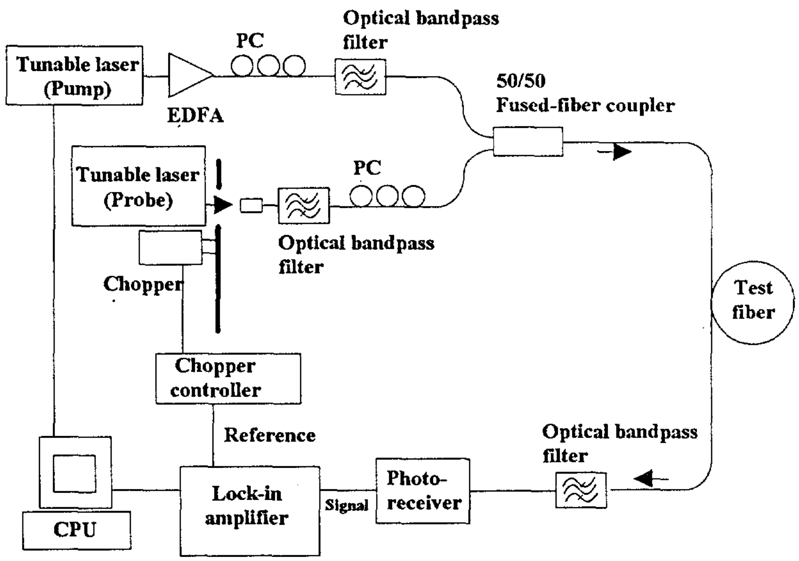

Figure 1. Experimental configuration for obtaining FWM efficiency: PC, polarization controller; CPU, personal computer.

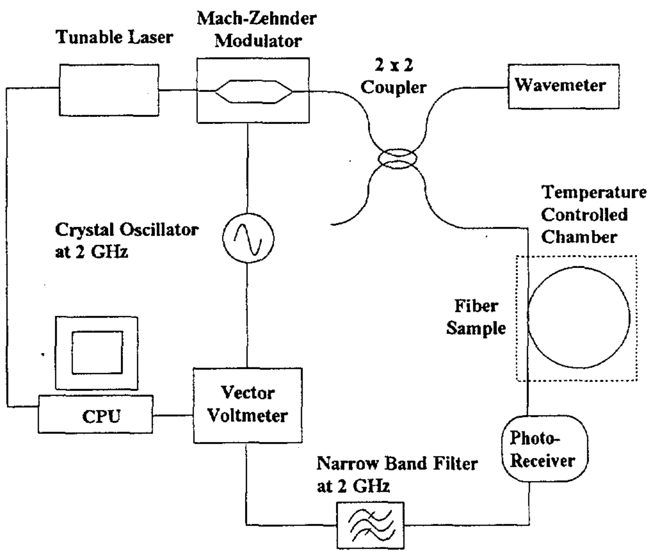

Figure 2. Frequency-domain phase shift system: CPU, personal computer.

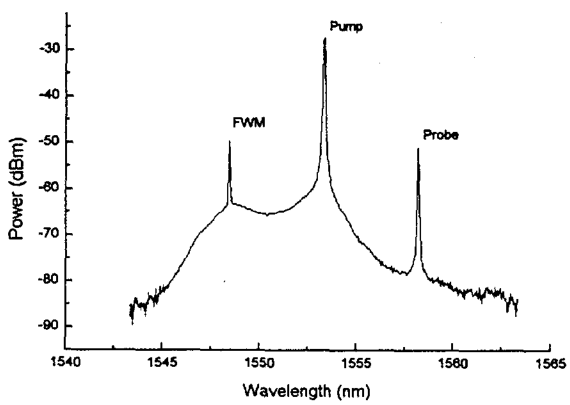

Figure 3. Partially degenerate FWM spectrum: FWM, four-wave mixing anti-Stokes peak.

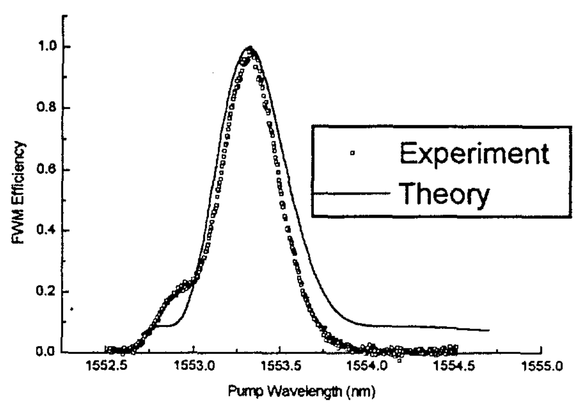

Figure 4. FWM efficiency versus wavelength in 10 km dispersion-shifted fiber. Mid-scan pump-probe separation is 7 nm.